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ABSTRACT

We present wavelength measurements of K-shell resonance lines of O V and O VI, using the University of California Lawrence Livermore National Laboratory EBIT-I electron beam ion trap. The wavelength accuracy of better than 140 ppm is sufficient to determine gas outflow velocities of warm absorbers associated with AGNs to within 40 km/s and better. Our measurements confirm that the outflow velocities associated with NGC 5548 and derived from the O V and O VI lines are similar to those derived from the O VII lines. These kinematic measurements make for further evidence that the X-ray and UV absorbers in these systems are truly two manifestations of the same physical outflow.

Subject headings: atomic data, galaxies: active, galaxies: outflow velocity

1. INTRODUCTION

Observations of Active Galactic Nuclei (AGNs) and their outflows are an important area of present astrophysical investigation (Alloin et al. 1995; Kaspi et al. 2001). Of particular interest are features in the EUV and soft-x-ray ranges that have become accessible only recently, by the *Chandra* and $XMM - Newton$ space telescopes. For example, inner-shell satellites in the spectra of the more abundant elements, like oxygen and iron, yield information about column density, velocity and spatial abundance of emitting and absorbing regions. With the powerful diffraction grating instruments on board *Chandra* (Brinkman et al. 1999) and *XMM-Newton* (den Herder et al. 2001), it is now possible to observe minute details of such spectra that have never been seen before, and exploit them for astrophysical analysis.

As the interpretation of UV absorption spectra of AGNs suffers from great difficulties due to velocity-dependent line saturation (e.g., Arav et al. (2003)), X-ray inner-shell absorption spectroscopy on ions of the same charges state has the potential of providing complementary and perhaps better physical measurements for these sources. However, the uncertainty in the rest frame wavelengths of the X-ray lines has hampered observers (Behar & Kahn 2002). Only when these wavelengths are known, it is possible to determine wavelength shifts in the astrophyscial data. Wavelength predictions by various calculations for the resonance lines in O V and O VI differ by as much as 50 mÅ (Behar & Kahn 2002). Such differences correspond to uncertainties of the emitter velocities of more than Δv $\approx$ 700 km/s, which is of the same order of magnitude as the full value of typical outflow velocities (Behar et al. 2003; Steenbrugge et al. 2003). Clearly, experimental data are needed to lock down the reference values. While accurate wavelength measurements exist for the K-shell transitions of O VII (Engström & Litzén 1995), wavelength data for the K-shell transitions of the lower charge states of oxygen (Gabriel 1972; Nicolosi & Tondello 1977) are less reliable, if available at all. In the following, we present laboratory measurements of the wavelengths of the O V and O VI soft-x-ray resonance lines with an accuracy of better than 140 ppm, which exceeds that of the *Chandra* and *XMM-Newton* data.

2. Measurement

The measurement employed the EBIT-I electron beam ion trap at the University of California Lawrence Livermore National Laboratory. The device has been used for laboratory astrophysics measurements for over a decade (Beiersdorfer 2003).

The present measurement utilized a high-resolution grazing incidence spectrometer with an angle of incidence of 1.5°. The spectrometer employs a variable line-spaced reflective grating with an average line spacing of 2400 grooves/mm and a radius of curvature of 44.3 m. The grating provides a nearly flat image field that permits the use of a two-dimensional charged coupled device (CCD) as a multichannel detector. The detector consists of a liquid-nitrogen cooled 27 mm × 26 mm, thinned, back-illuminated detector chip with 1340 × 1300 pixels of 20 μm × 20 μm nominal size; the quantum efficiency is about 45% at 22 Å. The detector size is sufficient to observe the wavelength range 21-28 Å in a given setting. The resolving power of the EBIT-I high-resolution grating spectrometer is about 1100.

Injecting carbon dioxide gas into the trap allowed us to observe lines from both oxygen and carbon. Lines of helium-like oxygen (O VII) and hydrogen-like carbon (C VI) served as *in situ* calibration lines. In particular, we observed the resonance (w), intercombination (y), and forbidden (z) lines of O VII (the single-letter line labels follow the convention defined by Gabriel (1972)). The wavelengths of these lines are well known from calculations by Drake (1988) and measurements by Engström & Litzén (1995). We also observed the LYMAN series in the hydrogen-like spectrum of C VI, L_β through L_ε, the wavelengths of which are well known from calculations by Garcia & Mack (1964). Each of these reference wavelengths is presumed to be accurate to 1 mÅ or better.

Figure 1 displays a typical spectrum of the oxygen K-shell emission in the range 21.4 - 22.6 Å. The spectrum was accumulated during a 120 min exposure. Ten such spectra were used to assess statistical and systematic errors. The spectrum shows the unresolved O VI resonance line doublet which originates from the 1s2s2p $^2P_{3/2,1/2} \rightarrow 1s^22s\ ^2S_{1/2}$ transitions. The two components are labeled q and r, respectively, in the notation of Gabriel (1972). This line doublet of O VI has not been resolved in any of the earlier studies (Gabriel 1972; Nicolosi & Tondello 1977), nor was the resolving power of our instrument high enough to achieve this.

The intensity ratio within the line doublet is expected to be approximately 2:1 both in emission and in absorption, based on that same ratio of the weighted oscillator strengths (gf), while the auto-ionization and radiative decay rates are roughly equal for the two levels. A similar line blend has been observed before at our electron beam ion trap device when studying N V (Beiersdorfer et al. 1999).

The spectrum also shows the O V K-shell line β which results from the transition $1s2s^22p\ ^1P_1 \rightarrow 1s^22s^2\ ^1S_0$. This line is very weak in comparison to the O VII and the (already much weaker) O VI lines. One of the reasons for this lies in the ionization balance; at the electron energies that are needed to excite K-shell lines, the charge state distribution strongly favors O VII, leaving only a small fraction of O VI and a minute abundance of O V. In fact, the ionization potential of O V is about 138 eV, while for technical reasons we used an electron beam energy of 4 keV. We therefore continually supplied neutral oxygen and then detected the O V and O VI lines during the ionizing phase, before the ionization equilibrium was reached. This procedure is similar to that used in our earlier measurement of the K-shell emission of low charge states of iron (Decaux et al. 1995, 1997).

Each spectrum was individually calibrated and analyzed. The variation of the line positions of the O V and O VI resonance lines was evaluated to yield a measure of the reproducibility and thus of the reliability of the wavelength data. The uncertainty of the reference line position was added in quadrature to the uncertainty of the line positions of the O V and O VI lines. The uncertainty of the reference line wavelength was added linearly, resulting in an overall uncertainty of 1.6 mÅ for the q,r-line blend and 3 mÅ for the β line. For the q,r-line blend the (systematic) uncertainty of the reference wavelengths and the actual measurement contribute about equally to this overall uncertainty. The larger value of the β line is derived from the fact that it is farther away from calibration lines and lower in intensity than the O VI lines. The wavelength values measured for the lines q, r, and β are given in Table 1.

3. COMPARISON TO EARLIER MEASURED VALUES, CALCULATIONS AND *CHANDRA-LETGS* OBSERVATION

In Table 1 we compare the new wavelength values of the inner-shell satellite lines q, r, and β to those reported earlier. The agreement for the q,r-line blend is excellent, but our values are better constrained. For the O V line β, we did not find any previous data in the literature. The atomic spectra database from the National Institute of Standards and Technology (NIST website) did not provide a value for either of the O V or O VI lines.

In Table 1 we also list results of various calculations. The theoretical values scatter notably, and without a measurement it is impossible to determine which one is accurate. In fact, only the calculations by Vainshtein & Safronova (1971, 1978) match both measured wavelengths, the q,r-line blend and the β line, well. Other calculations match neither line (Chen 1985, 1986) within the observational uncertainty, or match only one of the measured wavelengths (Behar & Kahn 2002; Pradhan et al. 2003). As noted by Behar & Kahn (2002), the wavelength spread of the theoretical predictions renders theoretical wavelengths too unreliable for evaluating AGN spectra. For example, a spread of 50 mÅ in the predicted wavelength of line β results in an uncertainty of Δv $\approx$ 700 km/s. In contrast, the line positions measured at the LLNL electron beam ion trap have uncertainties of 1.6 mÅ (q, r) and 3 mÅ (β), which corresponds to Δv $\approx$ 22 km/s and Δv $\approx$ 40 km/s, respectively. By comparison, the uncertainty of the *Chandra-LETGS* wavelength data is 10 mÅ, corresponding to Δv $\approx$ 120 km/s.

Table 1 also lists wavelengths of the q and r line blend and of the β line as given by Behar & Kahn (2002) who refer to a private communication from Kaastra on the AGN outflow observation of NGC 5548 using the *Chandra-LETGS* instrument (Kaastra et al. 2000; Arav et al. 2003). These particular wavelength values were obtained assuming that the outflow velocities of all ions are similar to that of the O VII velocity, the value of which is well known, as discussed above. That is, the wavelength shift derived from the O VII line position was used to determine the rest frame wavelength of the observed O V and O VI lines. The wavelengths so derived agree within the uncertainties with our laboratory data. This in turn corroborates the model assumption of similar outflow velocities for different ion species that was implied by Behar & Kahn (2002).

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		O VI q-r	O V β
Measurement	Gabriel (1972)	22.02	
	Nicolosi & Tondello (1977)	22.020±0.006	
	LLNL EBIT[a]	22.0194±0.0016	22.374±0.003
Calculation	Gabriel (1972)	22.02	
	Vainshtein & Safronova (1971, 1978)	22.02	22.38
	Chen (1985, 1986)	22.06	22.41
	Behar & Kahn (2002)	22.00	22.33
	Pradhan et al. (2003)	22.05	22.35
Observation	NGC 5548[b]	22.01±0.01	22.38±0.01

Table 1: Wavelengths in Å for the q,r and the β lines in oxygen.

[a]present work

[b]Kaastra, private communication; adjusted for outflow velocity derived from the O VII K-shell lines.

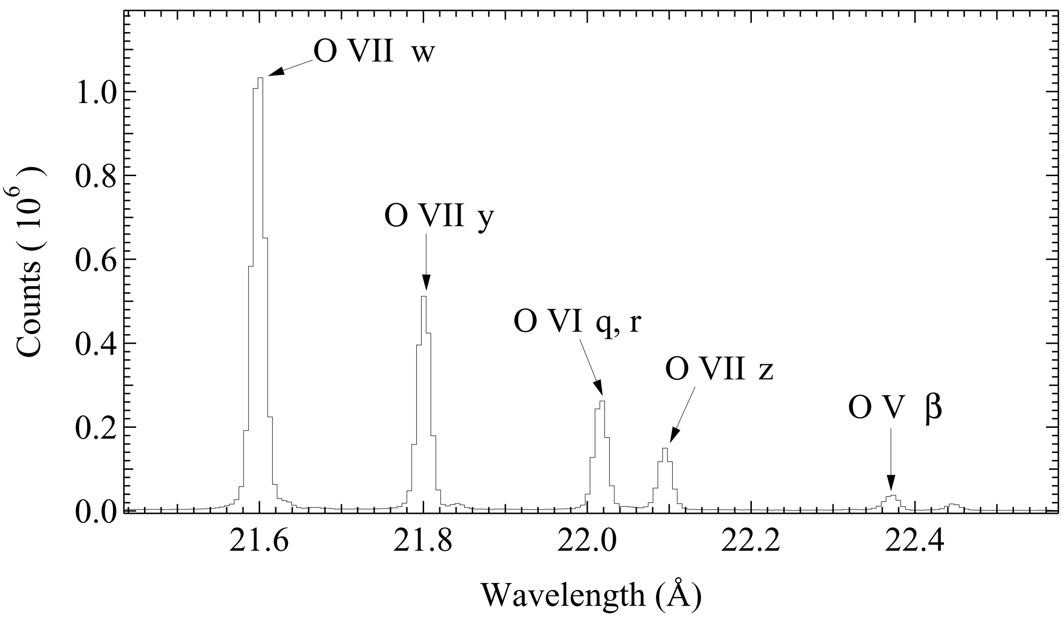

Fig. 1.— Oxygen spectrum recorded at the Livermore electron beam ion trap employing a flat-field soft-x-ray spectrometer. Exposure time 120 min. The line labeling by single letters follows the schematics proposed by Gabriel (1972).